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6 MANEUVERING PERFORMANCE OF HIGH-SPEED SHIPS WITH EFFECT OF ROLL MOTION.

10 by Haruzo Eda

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15 Prepared for
Office of Naval Research
Contract N00014-67-A-0202-0040
(DL Project 4007/143)

STEVENS INSTITUTE OF TECHNOLOGY

CASTLE POINT STATION
HOBOKEN, NEW JERSEY 07030

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SHIP MANEUVERING
SHIP COURSE STABILITY
SHIP HYDRODYNAMICS
SHIP STEERING
SHIP ROLLING

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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ABSTRACT (Cont'd)

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viii + 10 pp.
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Equations of yaw, sway, roll and rudder motions are formulated to represent realistic maneuvering behavior of high-speed ships such as destroyers. Important coupling terms between yaw, sway, roll and rudder were included on the basis of recent captive model test results of a high-speed ship. A series of computer runs was made by using the equations of yaw, sway, roll and rudder motions. Results indicate substantial coupling effects between yaw, roll, and rudder, which introduce changes in maneuvering characteristics and reduce course stability in high-speed operation. These effects together with relatively small GM (which is typical for certain high-speed ships) produce large rolling motions in a seaway as frequently observed in actual operations. Results of digital simulations and captive model tests clearly indicate the major contributing factors to such excessive rolling motions at sea.

KEYWORDS

Ship Maneuvering
Ship Course Stability
Ship Hydrodynamics
Ship Steering
Ship Rolling

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NOMENCLATURE

A	reference area ($A = \ell H$, ℓ^2, or BH)
a	yaw gain constant
B	ship beam
b	yaw-rate gain constant
c	sway gain constant
d	sway-rate gain constant
D_w	water depth
e	subscript e indicates the value at the equilibrium condition
F_r	Froude number ($U/\sqrt{g\ell}$)
g	acceleration due to gravity
H	ship draft
I_z	moment of inertia referred to z-axis
ℓ	ship length
m	mass of ship
N	hydrodynamic and aerodynamic yaw moment
$N_{\dot{r}}$	derivative of hydrodynamic yaw moment with respect to yaw acceleration
N_v	derivative of hydrodynamic yaw moment with respect to sideslip velocity
n	propeller revolutions per second
N_δ	derivative of hydrodynamic yaw moment with respect to rudder angle
r	yaw rate
t_r	time constant of rudder in control system
U	ship speed ($U = \sqrt{u^2+v^2}$)
u	component of ship speed along x-axis

v component of ship speed along y-axis

X hydrodynamic and aerodynamic force component in x-axis direction

X_p hydrodynamic force component along x-axis due to propeller

$X_{\dot{u}}$ derivative of hydrodynamic force component along x-axis with respect to surge acceleration

X_{vr} second derivative of hydrodynamic force component along x-axis direction with respect to sideslip velocity and yaw angular velocity

X_o total resistance along x-axis

Y hydrodynamic and aerodynamic force component along y-axis

Y_r derivative of hydrodynamic force component along y-axis with respect to yaw rate

Y_v derivative of hydrodynamic force component along y-axis with respect to sideslip velocity

$Y_{\dot{v}}$ derivative of hydrodynamic force component along y-axis with respect to sideslip acceleration

Y_δ derivative of hydrodynamic force component along y-axis with respect to rudder angle

β drift angle ($-\sin^{-1} \frac{v}{U}$)

δ rudder angle

ψ heading angle of ship

Dimensionless Forms

Most dimensionless expressions in this paper follow SNAME nomenclature. The dimensionless form of a quantity is indicated by the prime of that quantity. Examples are shown below:

Quantity	Typical Symbol	Typical Dimensionless Form
Length	y_o	$y_o' = y_o/\ell$
Force	Y	$Y' = Y/\frac{\rho}{2} AU^2$
Moment	N	$N' = N/\frac{\rho}{2} A\ell U^2$
Mass	m	$m' = m/\frac{\rho}{2} A\ell$

Quantity	Typical Symbol	Typical Dimensionless Form
Angular velocity	r	$r' = r\ell/U$
Static force rate	Y_v	$Y_v' = Y_v/\frac{\rho}{2} AU$
Static moment rate	N_v	$N_v' = N_v/\frac{\rho}{2} A\ell U$
Rudder force rate	Y_δ	$Y_\delta' = Y_\delta/\frac{\rho}{2} AU^2$
Damping force rate	Y_r	$Y_r' = Y_r/\frac{\rho}{2} A\ell U$
Damping moment rate	N_r'	$N_r' = N_r/\frac{\rho}{2} A\ell^2 U$
Inertial coefficient	$Y_{\dot{v}}$	$Y_{\dot{v}}' = Y_{\dot{v}}/\frac{\rho}{2} A\ell$
Inertial coefficient	$N_{\dot{v}}$	$N_{\dot{v}}' = N_{\dot{v}}/\frac{\rho}{2} A\ell^3$
Moment of inertia	I_z	$I_z' = I_z/\frac{\rho}{2} A\ell^3$
Velocity	u	$u' = u/U$
Time	t	$t' = tU/\ell$

INTRODUCTION

When a ship is proceeding at a high-speed in a seaway, serious rolling motions are frequently observed in actual ship operations and in model testing in waves[1,2] Anomalous behavior of rolling and steering was clearly evident, for example, in full-scale tests of a high-speed container ship during cross-Atlantic operations[1].

Certain Naval ships have the following hull form characteristics which have major impacts on ship performance in particular, maneuvering and rolling behavior:

(1) High speeds with large ℓ/B ratio and relatively small GM.
(2) Fore-and-aft asymmetry
(e.g., with a sonar dome at the bow, see Figure 1)[3].
(3) Relatively large rudder.

This particular hull form characteristics introduces the possibilities of fairly significant yaw-sway-roll-rudder coupling effects during high-speed operations.

The major objective of this study is to examine the coupled motions of yaw, sway, roll and rudder for high-speed ships (e.g., hull forms similar to destroyers) through digital simulation studies.

Due to lack of available hydrodynamic data, no extensive digital simulation effort has been made previously, in the area of maneuvering performance with inclusion of roll motion effect which should have an important impact during high-speed operations. Recently, under other simultaneous research program at Davidson Laboratory, a high-speed ship was extensively tested in the rotating-arm facility with inclusion of roll motion effect. Test results clearly indicated fairly significant couplings between yaw-sway-roll-rudder motions. Accordingly, a mathematical model was formulated on the basis of these experimental results combined with analytical estimations, for a 500 ft long hull form which is similar to that of high-speed naval ships.

A series of computer runs were made by using equations of yaw, sway, roll and rudder motions on a digital computer.

Results indicated substantial coupling effects between yaw, sway, roll and rudder, which introduce changes in maneuvering and rolling behavior. For example, coupling terms introduce destabilizing effects on course stability and increase turning performance at high-speeds. These coupling effects together with relatively small GM produce large rolling motions in operations in seaways. Effects of yaw- sway- roll-rudder coupling on the possibility of yaw-roll instability were clearly demonstrated in simulation results.

This report has been prepared for the Office of Naval Research under Contract N00014-67-A-0202-0040. (DL Project 4007/143).

HULL CONFIGURATIONS

A high-speed hull form to be considered in this study includes the following characteristics as shown in a table below:

(1) High length-beam ratio and relatively small GM for high-speed operation.

(2) Fore-and-aft asymmetry, which is more pronounced for naval ships with appendages than that for commercial ships.

(3) Relatively large rudder.

Length, ℓ_{pp}, ft	500.0
Beam at WL, B, ft	60.0
Draft, H, ft	17.0
Rudder Area Ratio, Ar/ℓ_H	1/40
Block Coefficient, C_b	0.56

The above mentioned hull-form characteristics introduces a fairly substantial hydrodynamic coupling effects between yaw-sway-roll-rudder motions.

Figure 2 shows two curves which indicate the distance of CG of the local sectional area from the longitudinal centerline at roll angle ϕ = 0 and 15 degrees. The curves can be considered to be equivalent to camberline of the wing section.

Figure 3 shows the other example of the camberline for the hull form shown in the top of the figure.

When roll angle is not zero, the camberline is not straight line, as shown in these figures introducing hydrodynamic yaw moment and side force. This trend is pronounced by the fore-and-aft asymmetry of hull form, in particular, during high-speed operation.

Figure 4 shows, for example, captive model test results of yaw-roll coupling effect, indicating hydrodynamic yaw moment to port introduced by roll angle to starboard.

BASIC EQUATIONS FOR YAW-SWAY-ROLL-RUDDER MOTIONS

On the basis of captive model test results together with analytical estimations, an effort was made to formulate the equations of yaw-sway-roll-rudder motions to represent realistic maneuvering and rolling behavior of a high-speed ship.

Figure A-1 shows the coordinate system used to define ship motions with major symbols which follow the nomenclature used in previous papers. Longitudinal and transverse horizontal axes of the ship are represented by the x- and y- axes with origin fixed at the center of gravity. By reference to these body axes, the equations of motion of a ship in the horizontal plane can be written in the form:

$$
\begin{aligned}
I_z\dot{r} &= N && \text{(Yaw)} \\
I_x\ddot{\phi} &= K && \text{(Roll)} \\
m(\dot{v}+ur) &= Y && \text{(Sway)} \\
m(\dot{u}-vr) &= X && \text{(Surge)}
\end{aligned}
\qquad (1)
$$

where N, K, Y, and X represent total hydrodynamic terms generated by ship motions, rudder and propeller.

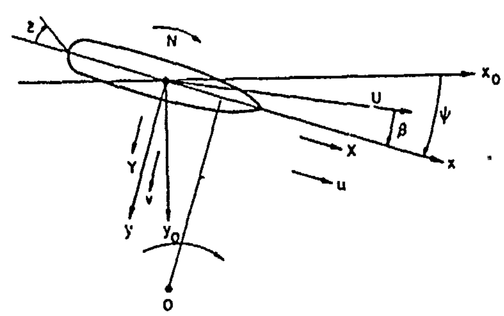

Figure A-1. Orientation of Coordinate Axes Fixed in Ship

Hydrodynamic forces are expressed in terms of dimensionless quantities, N', K', Y', and X' based on non-dimensionalizing parameters ρ (water density), U (resultant ship velocity relative to the water), and A, i.e.,

$$N' = \frac{N}{\frac{\rho}{2} U^2 A \ell} \quad , \quad Y' = \frac{Y}{\frac{\rho}{2} U^2 A} \quad , \quad \text{etc.} \qquad (2)$$

Hydrodynamic coefficients vary with position, attitude, rudder angle, propeller revolution, and velocity of the ship, For example, in the case of hydrodynamic yaw moment coefficient,

$$N' = N'(v', r', \delta, y_o', \dot{v}', \dot{r}', n', u', \varphi, \dot{\varphi}', \ddot{\varphi}') \qquad (3)$$

where

$$v' = \frac{v}{U}, \; r' = r\frac{\ell}{U}, \; y_o' = \frac{y_o}{\ell}, \; n' = \frac{n}{n_e}, \; u' = \frac{u}{u_e}, \; \text{etc.}$$

Finally, the following polynomials were obtained for predictions of ship dynamic motions:

$$N' = a_1+a_2v'+a_3r'+a_4\delta+a_5y_o'+a_6v'^2r'+a_7v'r'^2+a_8v'^3+a_9r'^3+a_{10}\delta^3$$
$$+a_{11}y_o'^3+a_{12}\dot{r}'+a_{13}\dot{v}'+a_{14}\varphi+a_{15}\dot{\varphi}'+a_{16}\ddot{\varphi}'$$

$$Y' = b_1+b_2v'+b_3r'+b_4\delta+b_5y_o'+b_6v'^2r'+b_7v'r'^2+b_8v'^3+b_9r'^3+b_{10}\delta^3$$
$$+b_{11}y_o'^3+b_{12}\dot{r}'+b_{13}\dot{v}'+b_{14}\varphi+b_{15}\dot{\varphi}'+b_{16}\ddot{\varphi}'$$

$$X' = c_1+c_2v'r'+c_3v'^2+c_4\delta^2+c_5\dot{u}'+X_p'$$

$$K' = d_1+d_2v'+d_3r'+d_4\delta+d_5\varphi+d_6\dot{\varphi}'+d_7\dot{\varphi}'^3+d_8\ddot{\varphi}'+d_9\dot{v}' \qquad (4)$$

ROLL-YAW COUPLED INSTABILITY

Figure 5 shows roll extinction curves obtained in simulation runs on a straight course at 30 knots having GM values of 3 ft and 2 ft. This particular result was obtained in the roll equation uncoupled from yaw and sway equations. The roll response shown in the figure can be considered to be realistic on the basis of comparison with results obtained from model tests of a similar high-speed ship shown in the same figure.

When roll extinction curves were obtained in simulation runs in equations of roll-yaw-sway coupled motions, an important change in rolling and yawing behavior was taken place. Roll-yaw coupled instability was clearly indicated in test runs. Figure 6 shows time history of roll and yaw motions starting on a straight course at 30 knots with an initial roll angle of 10 degrees. The roll extinction curve is approximately the same as that shown in the previous figure at the initial portion of the run. However, subsequent roll and yaw motions are divergent, indicating roll-yaw coupled instability. When an autopilot is adequately included in these yaw-sway-roll coupled motions, stability characteristics of the ship system is improved as shown in Figure 7, where the above mentioned roll-yaw instability is eliminated.

PREDICTIONS OF RESPONSE TO TURNING AND Z-MANEUVERS

Figures 8 and 9 show response to 20°-20° Z-maneuver having GM of 3.0 and 25.0 feet. The approach speed is 30 knots in the tests. A comparison of heading angle response is shown in Figure 8, which clearly indicates a greater overshoot angle with GM of 3.0 feet relative to that with GM of 25.0 feet. It is clearly evident in this figure that course stability characteristics are deteriorated with reduction in GM. Figure 9 shows a substantial difference in rolling behavior with GM of 3 and 25 feet. It should be noted in this figure that the largest roll angle is generated for the case of GM of 3.0 feet when the rudder angle is shifted to the other direction. This clearly indicates that the rudder angle has a counteracting effect to outward heel angle during steady turning.

Figures 10 and 11 show computer-plotted turning and rolling characteristics in deep water. The major parameter changes in computer runs were as follows:

1. Rudder Angle = 35°
2. GM = 2.0', 3.0', 25.0'

Roll angle during enter-a-turn is shown, for example, in Figure 11, which confirms very well previous full-scale observations.

Figures 10 and 11 clearly show the effect of GM on turning and rolling characteristics. Substantial changes in maneuvering characteristics (i.e., reduction in course-keeping and increase in turning performance) are clearly evident in these figures with a decrease in GM.

YAW-SWAY-ROLL-RUDDER COUPLED MOTIONS WITH AUTOPILOT

Roll-yaw coupled instability was clearly indicated in yaw-sway-roll coupled motions in the previous test runs. In actual ship operations, rudder is actively used, introducing important effects on yaw-sway-roll motions.

Let us consider the ship dynamic behavior under the following conditions:

When the ship is proceeding on a straight course, a certain external disturbance (e.g., the roll moment due to beam wind) is given stepwise to the ship. When the ship is rolled to the starboard, for example, due to beam wind from the port, an asymmetry is formed in the underwater

portion of the hull as shown in the previous figure (i.e., Figure 2). As a result, hydrodynamic yaw moment is generated to deviate the ship heading to the port. Subsequently, the rudder is activated by the auto-pilot to the starboard to correct heading angle deviation. This starboard rudder angle produces the roll angle further to the starboard. Under this condition, the possibility of instability exists in the ship systems.

Accordingly, simulations were carried out under the following conditions:

The 500 ft long ship was proceeding on a straight course at an approach speed of 30 knots. A stepwise roll moment (e.g., due to beam wind from the port) was given to the ship. The magnitude of the moment is equivalent to a statically generated roll angle of 5 degrees. The subsequent dynamic response of the ship was computed with inclusion of an autopilot system, which can be represented as:

$$\delta_d = a\ (\psi - \psi_d) + b'\dot{\psi}'$$

where δ_d = desired rudder angle

ψ_d = desired heading angle

a = yaw gain

b' = yaw-rate gain

Figures 12 and 13 show oscillatory motions for the case where GM = 2 ft, yaw gain = 3, and yaw-rate gain = 0. Instability of the ship systems is clearly evident in the figure.

When GM is increased to 3 ft, the stability characteristics is improved as shown in Figures 14 and 15.

When the autopilot is refined with addition of yaw-rate gain of 0.5, further improvement in the stability characteristics is shown in Figures 16 and 17. It should be noted here that the autopilot refinement substantially improved the rolling behavior as shown in these figures.

The results mentioned in the above clearly indicate the possibility of instability due to a stepwise disturbance. During actual operations in seaways, continuous disturbances are given to the ship due to wind and waves. Accordingly, even marginal yaw-roll-rudder instability can introduce serious rolling problems in seaways.

Such difficulties have been frequently indicated in full-scale observations and model tests.[1,2] Figure 18 shows, for example, the possibility of yaw instability obtained by J. F. Dalzell during model tests of a high-speed ship in waves.[2]

CONCLUDING REMARKS

The purpose of this study was to develop mathematical equations of yaw, sway, roll and rudder to represent realistic maneuvering behavior of high-speed naval ships, and subsequently to examine yawing and rolling motions during high-speed operations through a series of simulation runs.

Based on recent captive-model test results of a high-speed ship configuration, important coupling effects between yaw, sway, roll and rudder motions were included in the mathematical model. Certain terms such as yaw moment due to roll angle were not adequately considered in previous studies. It was found in this study that these terms have important impact on maneuvering and rolling behavior, introducing the possibilities of instability and serious rolling problems during high-speed operations in seaways.

The major findings obtained in this study are summarized as follows:

(1) Roll angle introduces asymmetry of underwater portion of hull form relative to the longitudinal centerline, which generates yaw moment due to roll (i.e., $N_\varphi \varphi$). This particular term introduces a tendency to turn to port when the ship is heeled to starboard, contributing to inherent yaw instability due to roll combined together with other coupling terms such as K'_v and K'_δ (i.e., roll-moment due to sideslip and rudder angle, respectively).

(2) When GM is relatively small (which is the case for most high-speed ships), the above-mentioned coupling terms can introduce severe rolling motions in a seaway. This was clearly indicated in substantial rolling motions during turning and Z-maneuvers.

(3) The possibility of yaw-roll instability exists for the ship system with autopilot during high-speed operations with small GM.

(4) Refinement in the autopilot characteristics has important effects on yawing and rolling behavior of the ship.

(5) Serious rolling problems frequently observed during high-speed operation in waves can partly be due to inherent yaw-roll instability (or marginal stability).

ACKNOWLEDGMENTS

The author wishes to thank Mr. J. F. Dalzell and Dr. A. Strumpf for their valuable discussions during various stages of this study.

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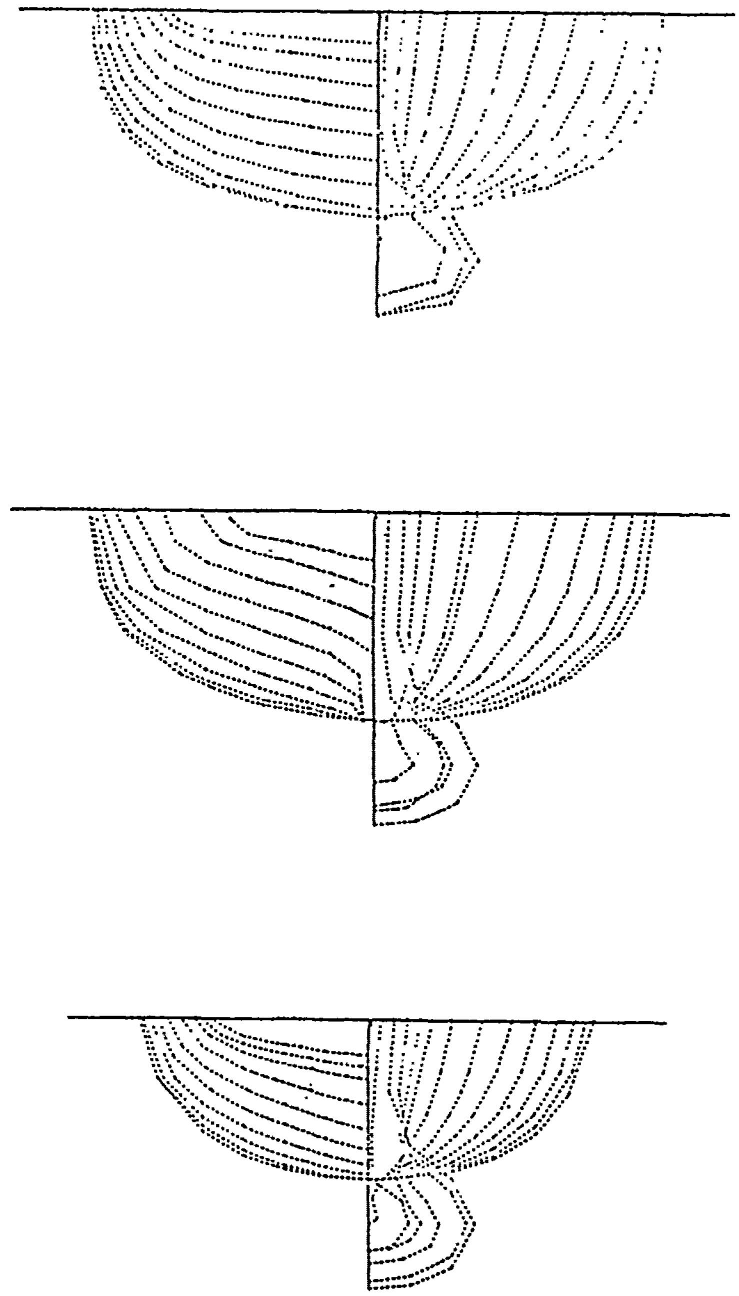


FIGURE 1. BODY PLANS OF REPRESENTATIVE NAVAL SHIPS

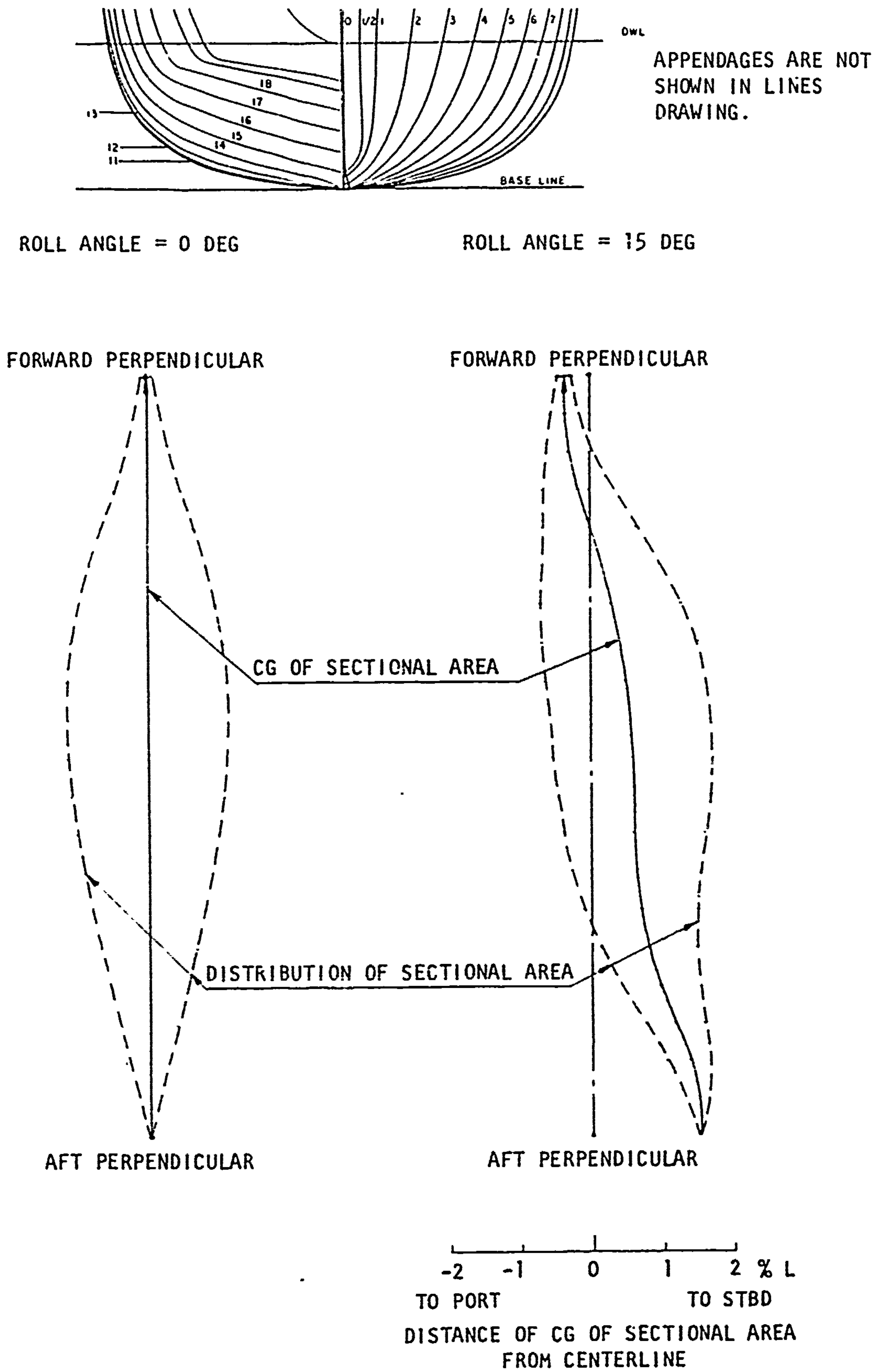


FIGURE 2. LONGITUDINAL ASYMMETRY DUE TO ROLL (DESTROYER)

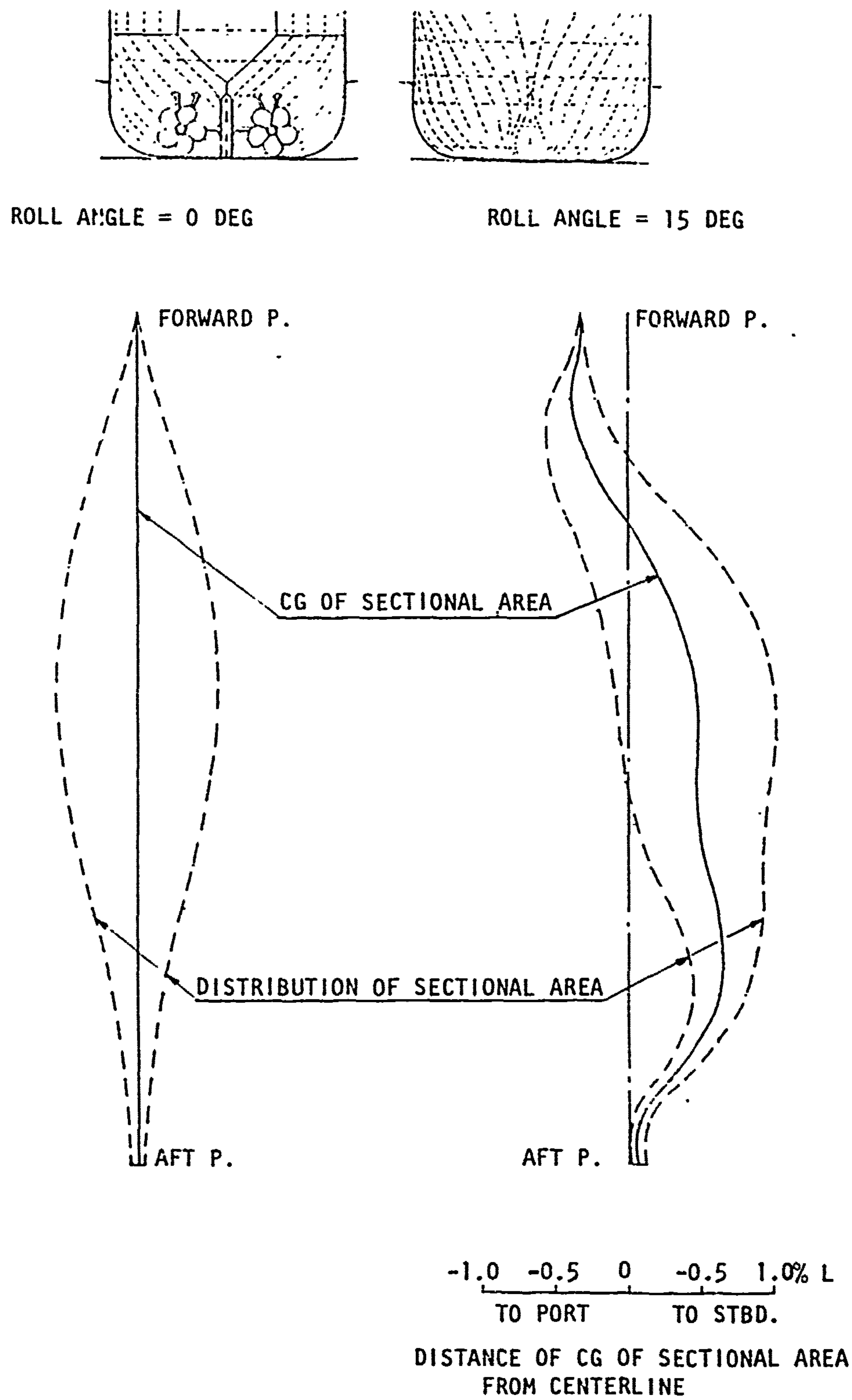


FIGURE 3. LONGITUDINAL ASYMMETRY DUE TO ROLL
(HIGH-SPEED CONTAINER SHIP)

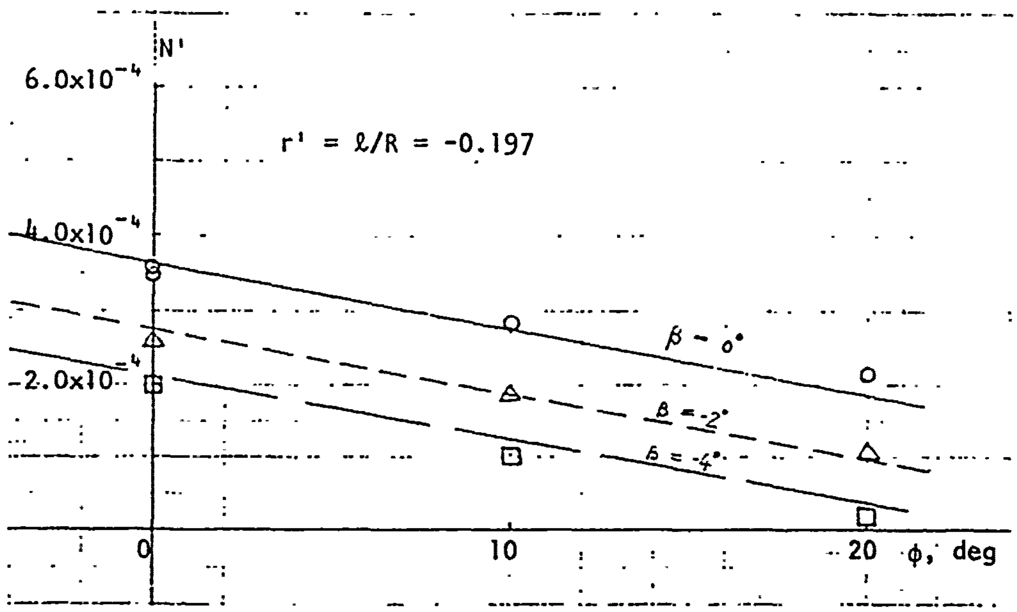
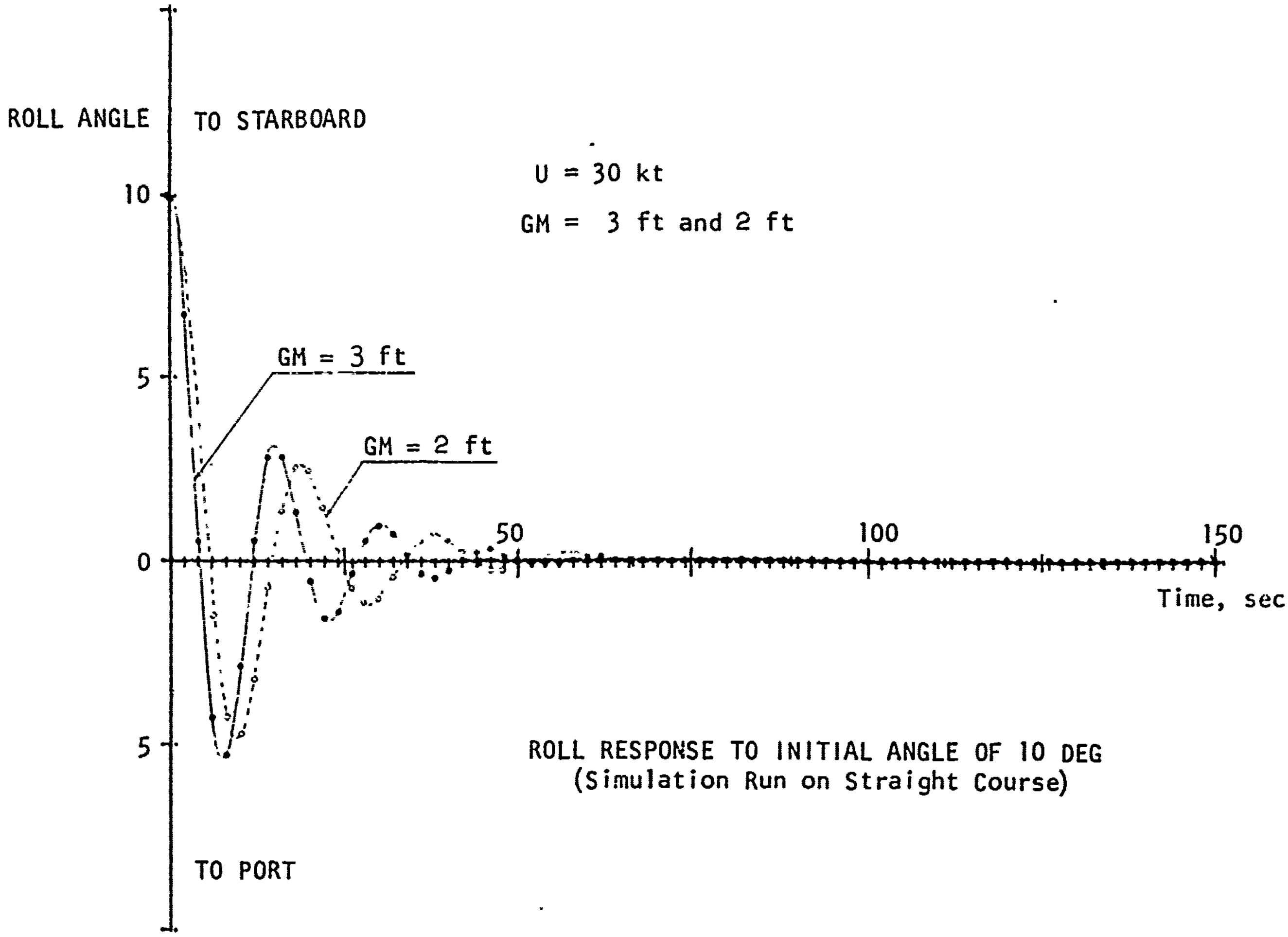
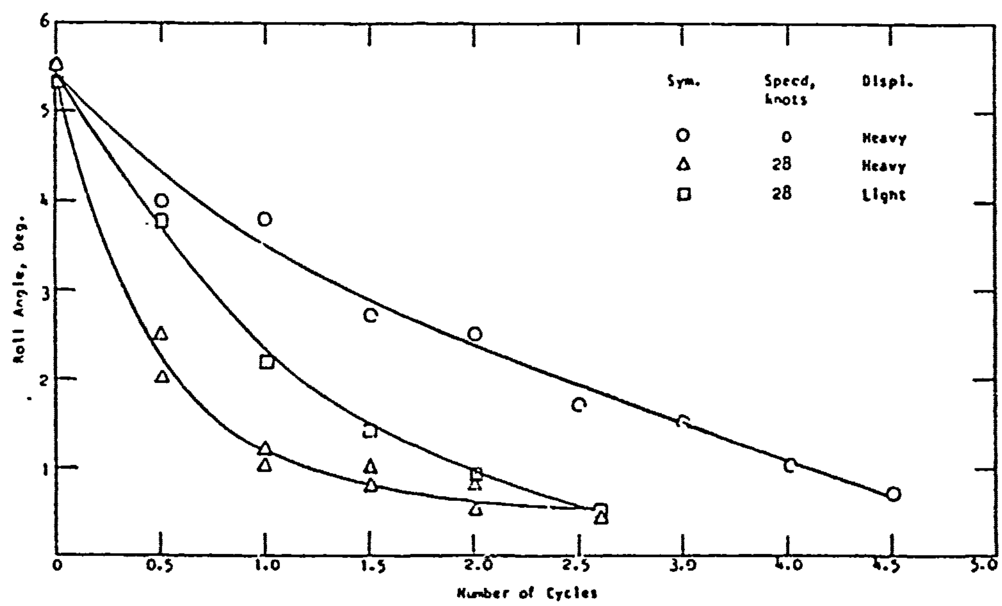


FIGURE 4. YAW MOMENT COEFFICIENT DUE TO ROLL ANGLE



ROLL RESPONSE TO INITIAL ANGLE OF 10 DEG
(Simulation Run on Straight Course)



ROLL RESPONSE TO INITIAL ROLL ANGLE
(6.29 FT MODEL TESTS)

FIGURE 5. ROLLING CHARACTERISTICS

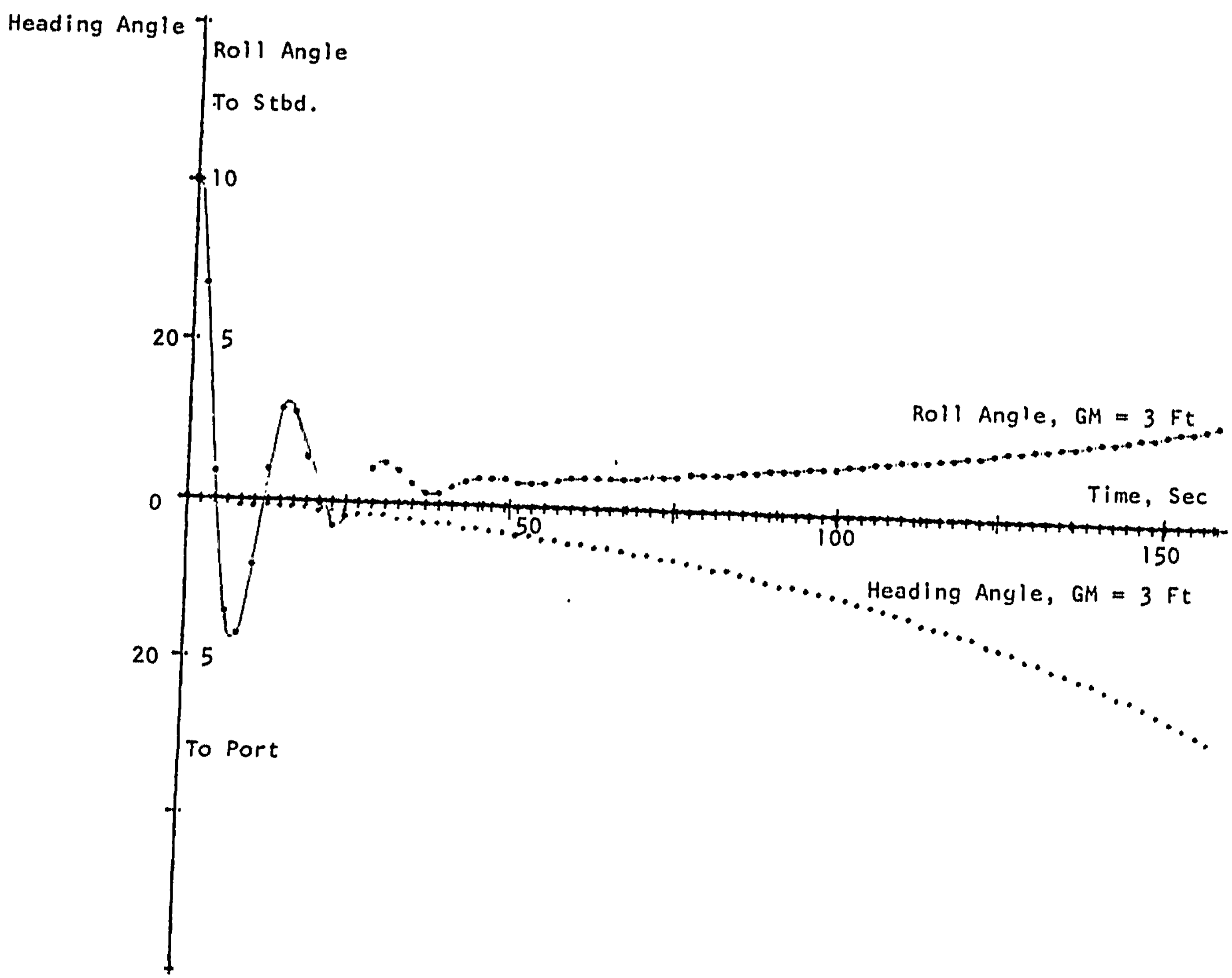


Figure 6. ROLL-YAW INSTABILITY
(WITH 10 DEG INITIAL DISTURBANCE)

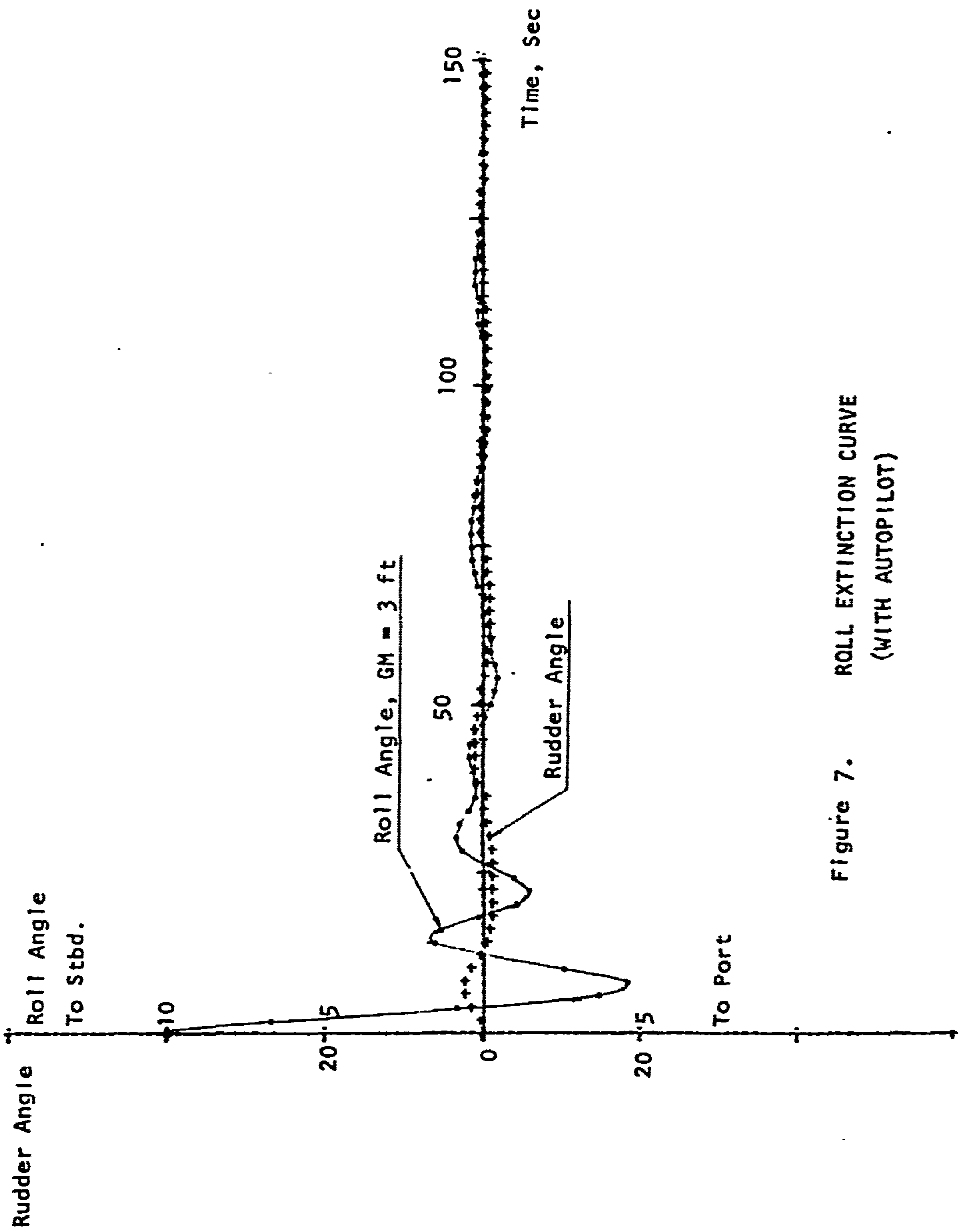


Figure 7. ROLL EXTINCTION CURVE (WITH AUTOPILOT)

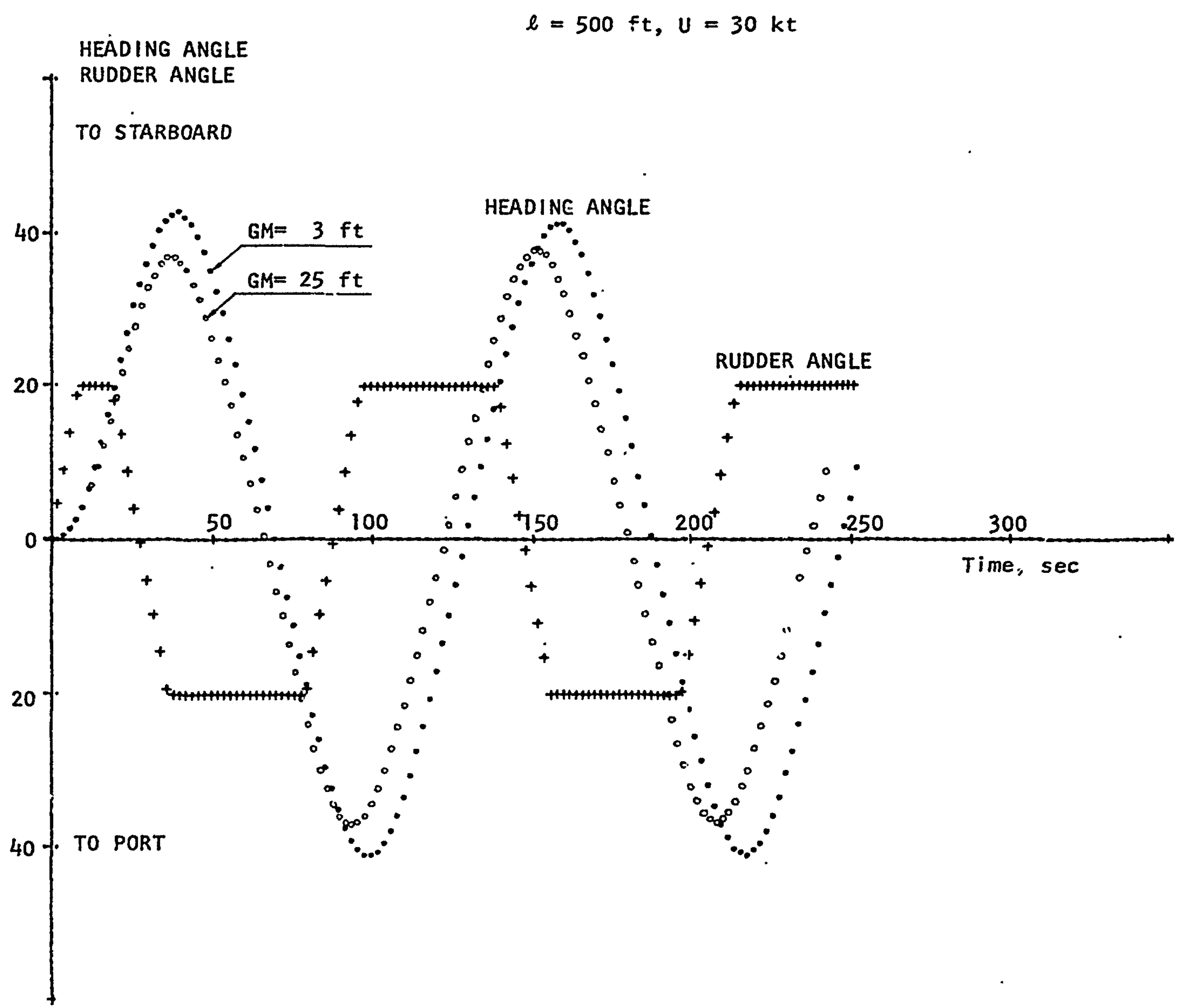


FIGURE 8. Z-MANEUVER RESPONSE

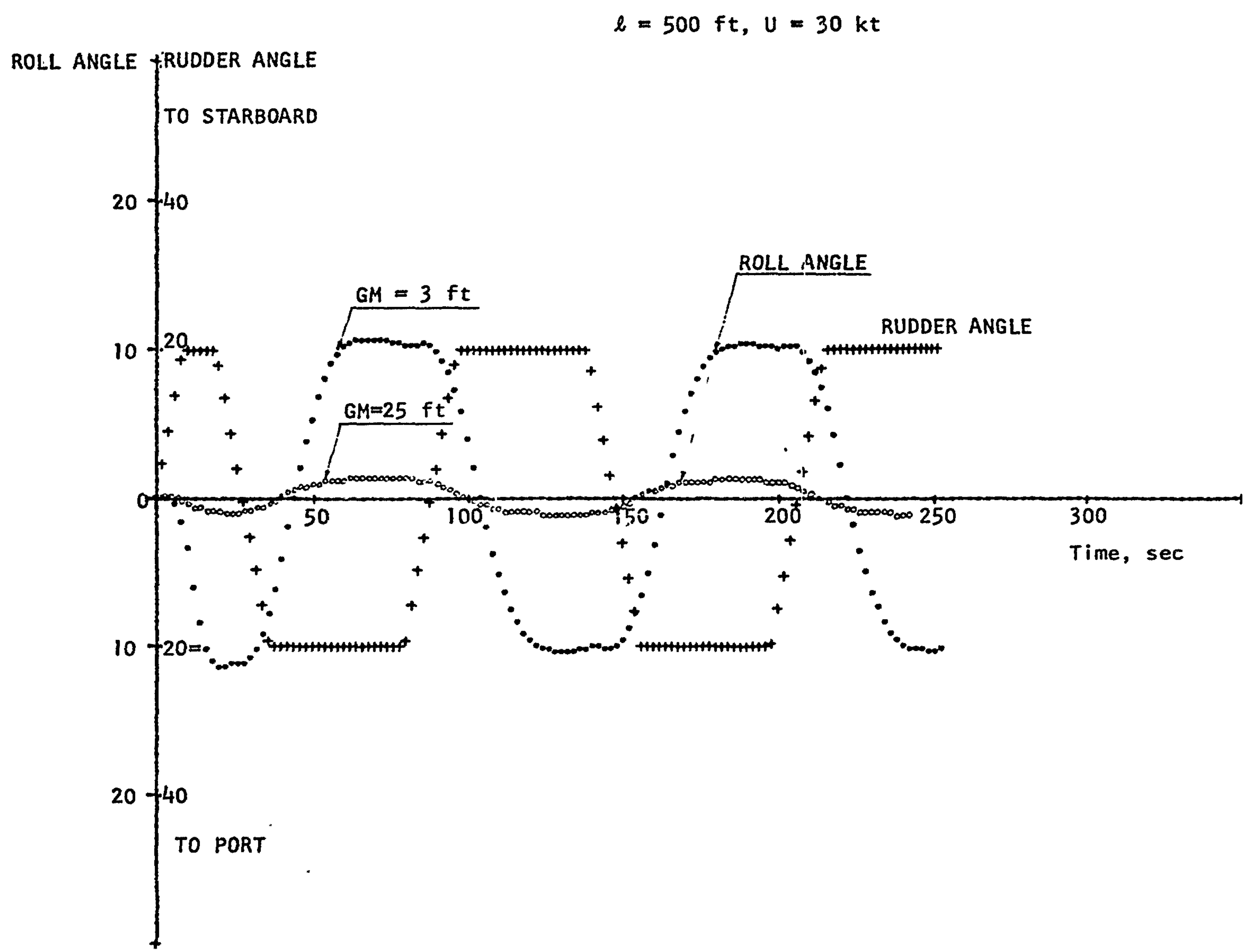


FIGURE 9. ROLL DURING Z-MANEUVER

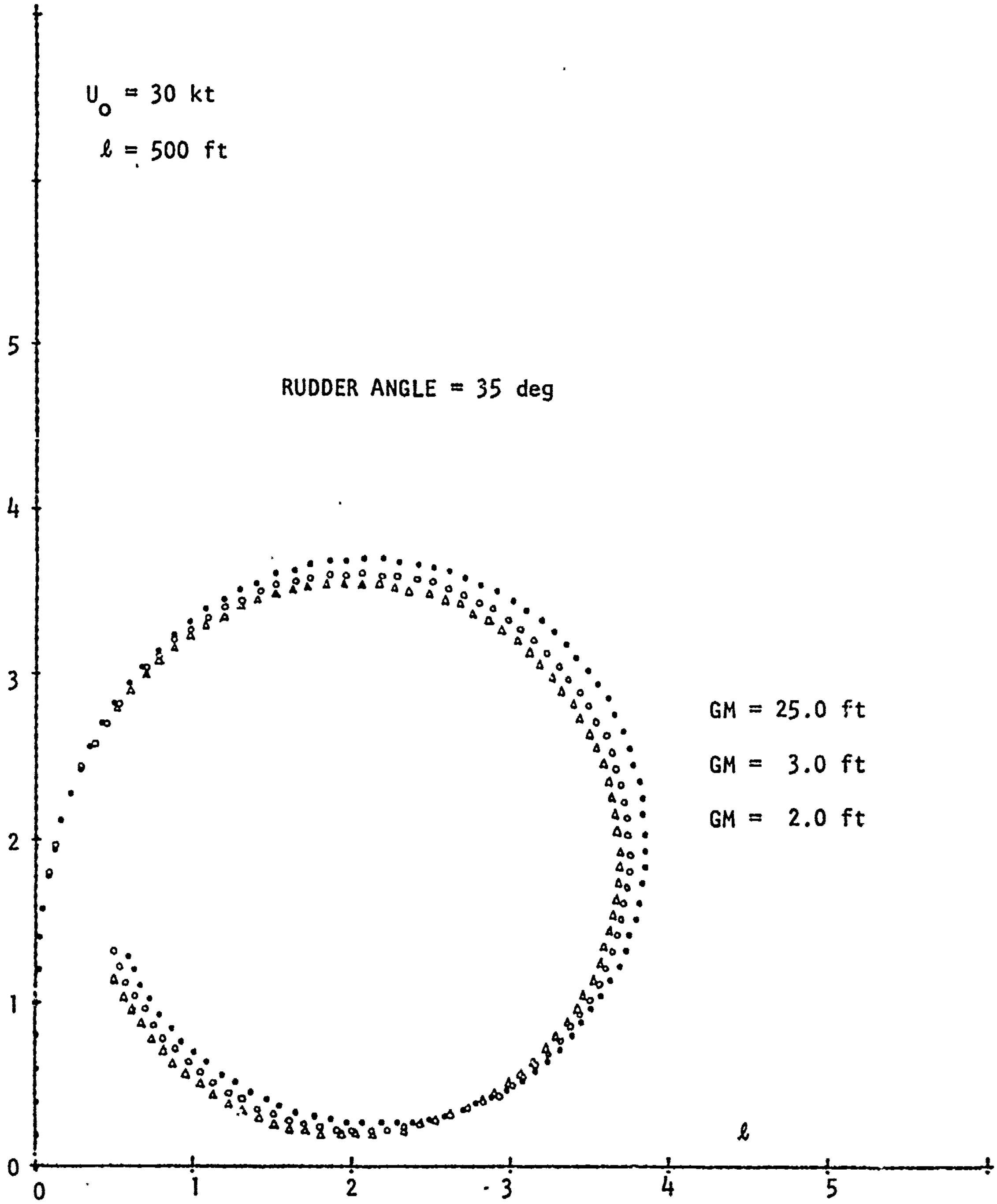


FIGURE 10. TURNING TRAJECTORY

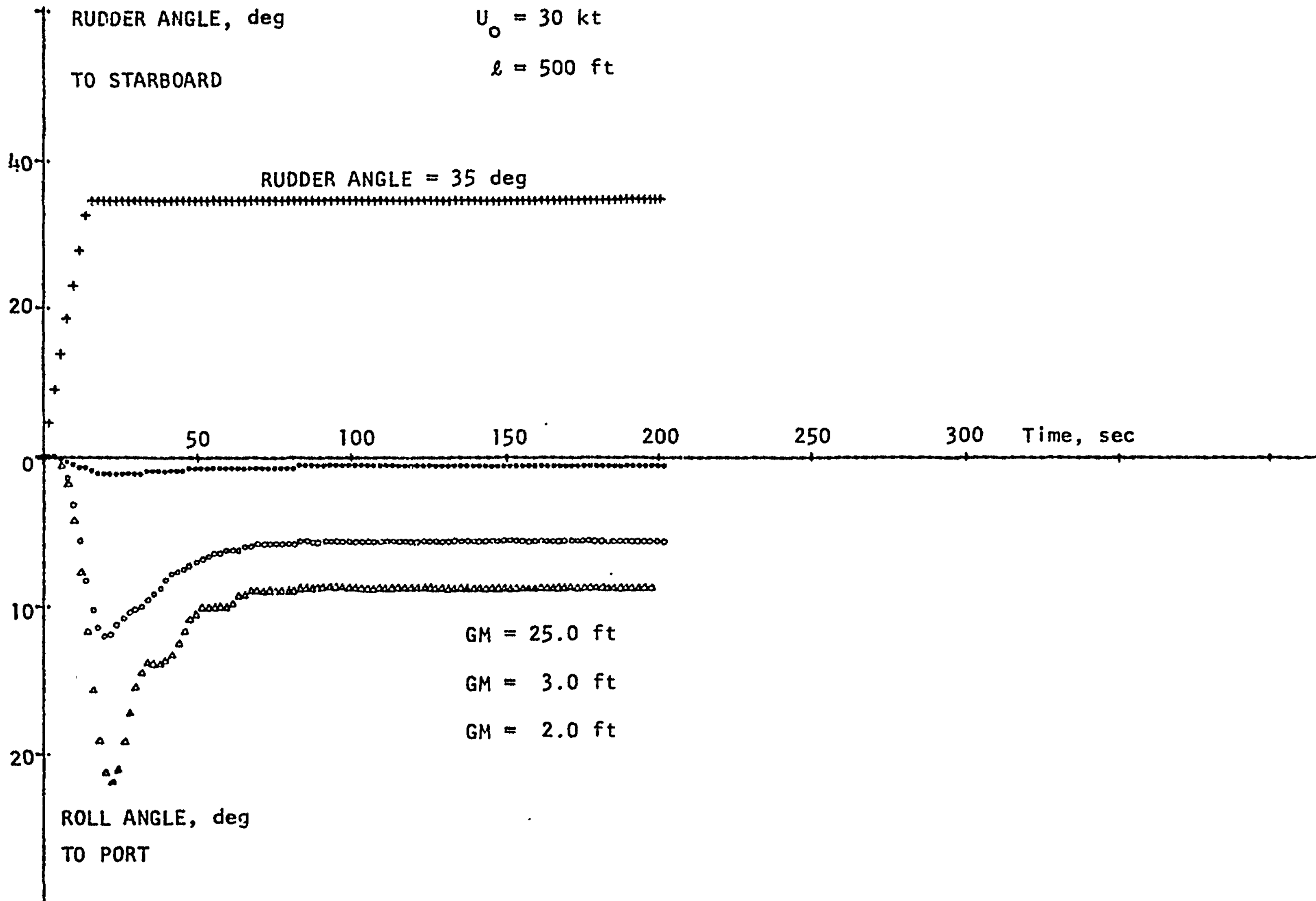


Figure 11. ROLL ANGLE DUE TO TURNING

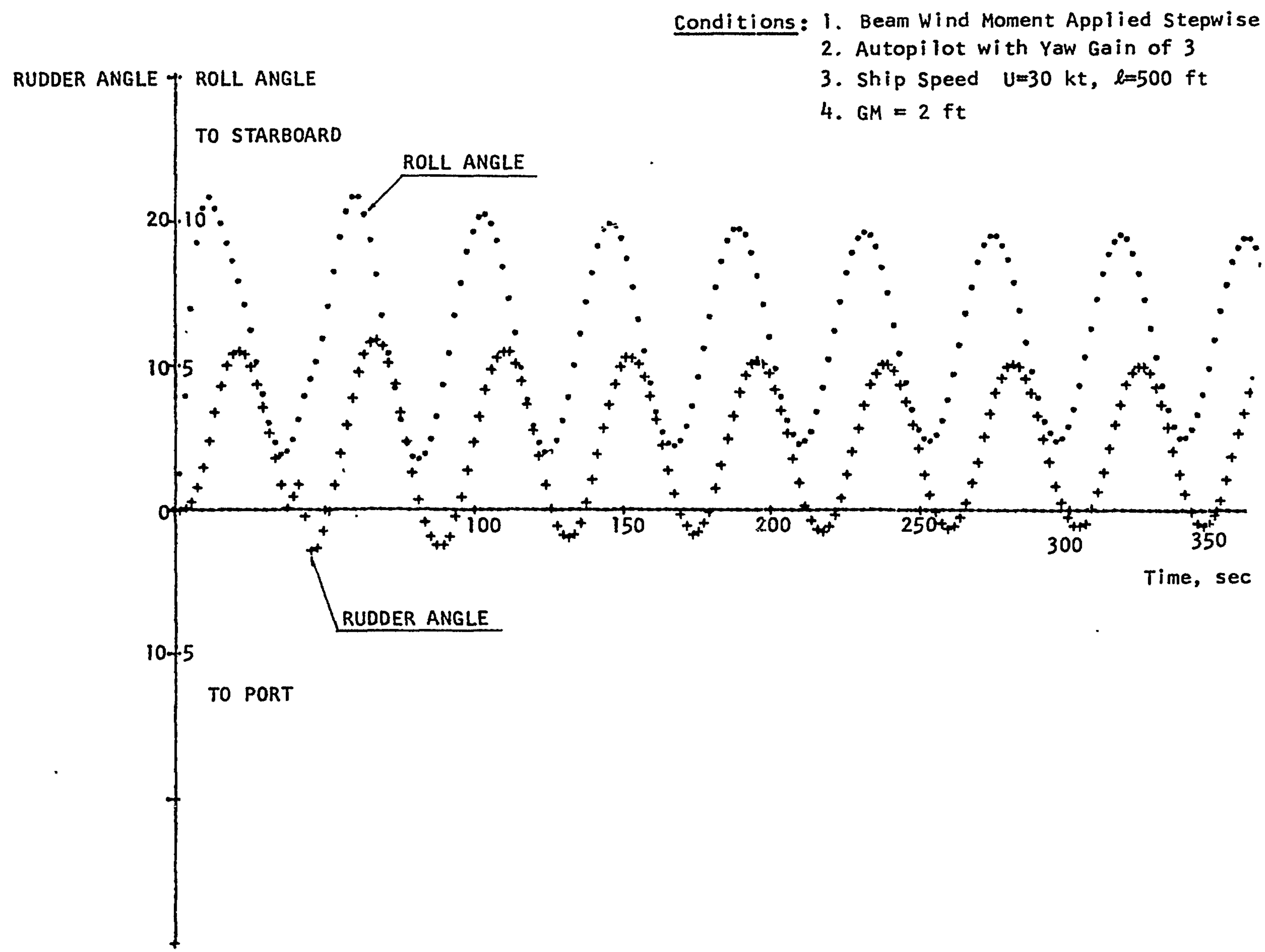


FIGURE 12. ROLL-YAW-RUDDER COUPLED MOTION

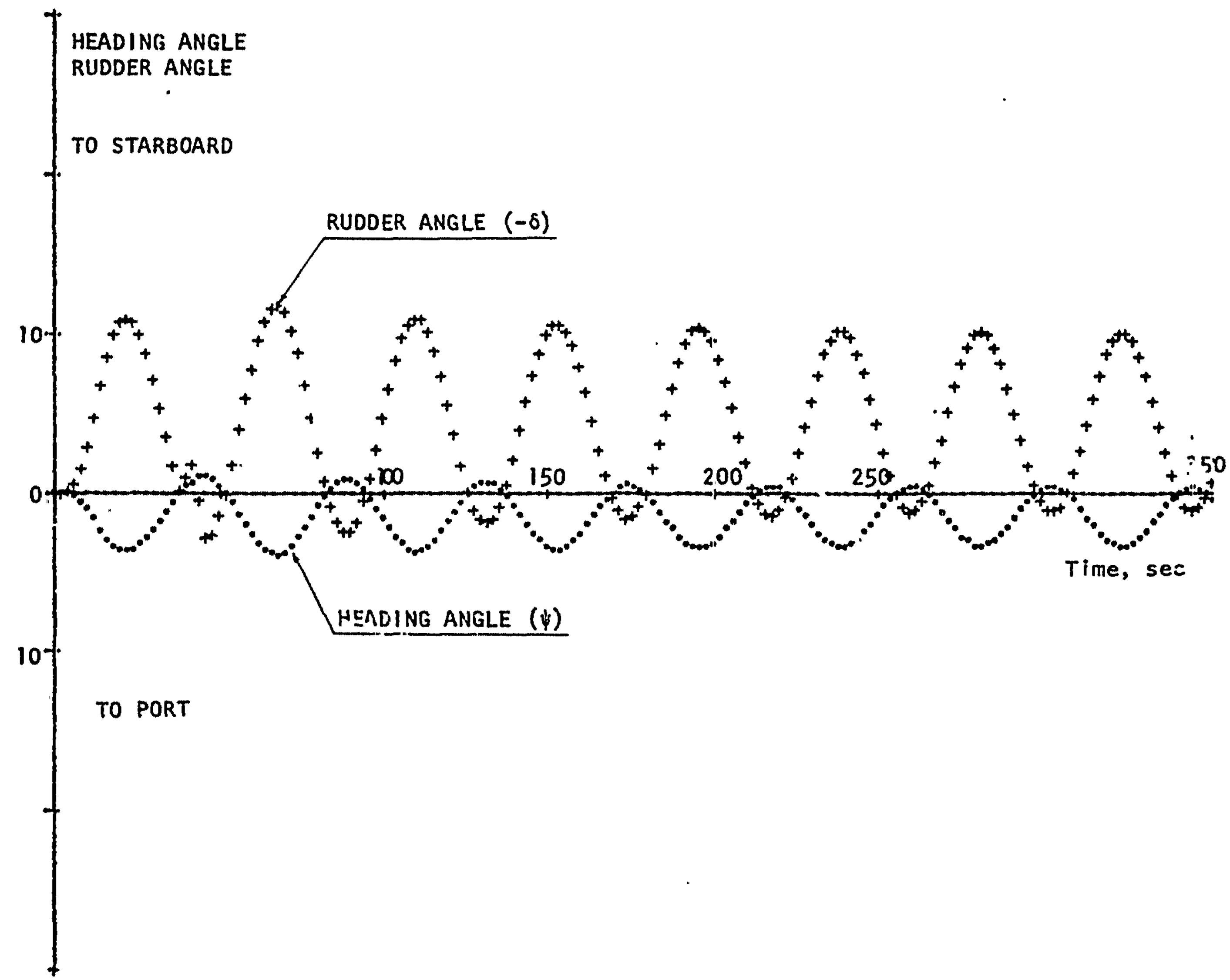


FIGURE 13. ROLL-YAW-RUDDER COUPLED MOTION

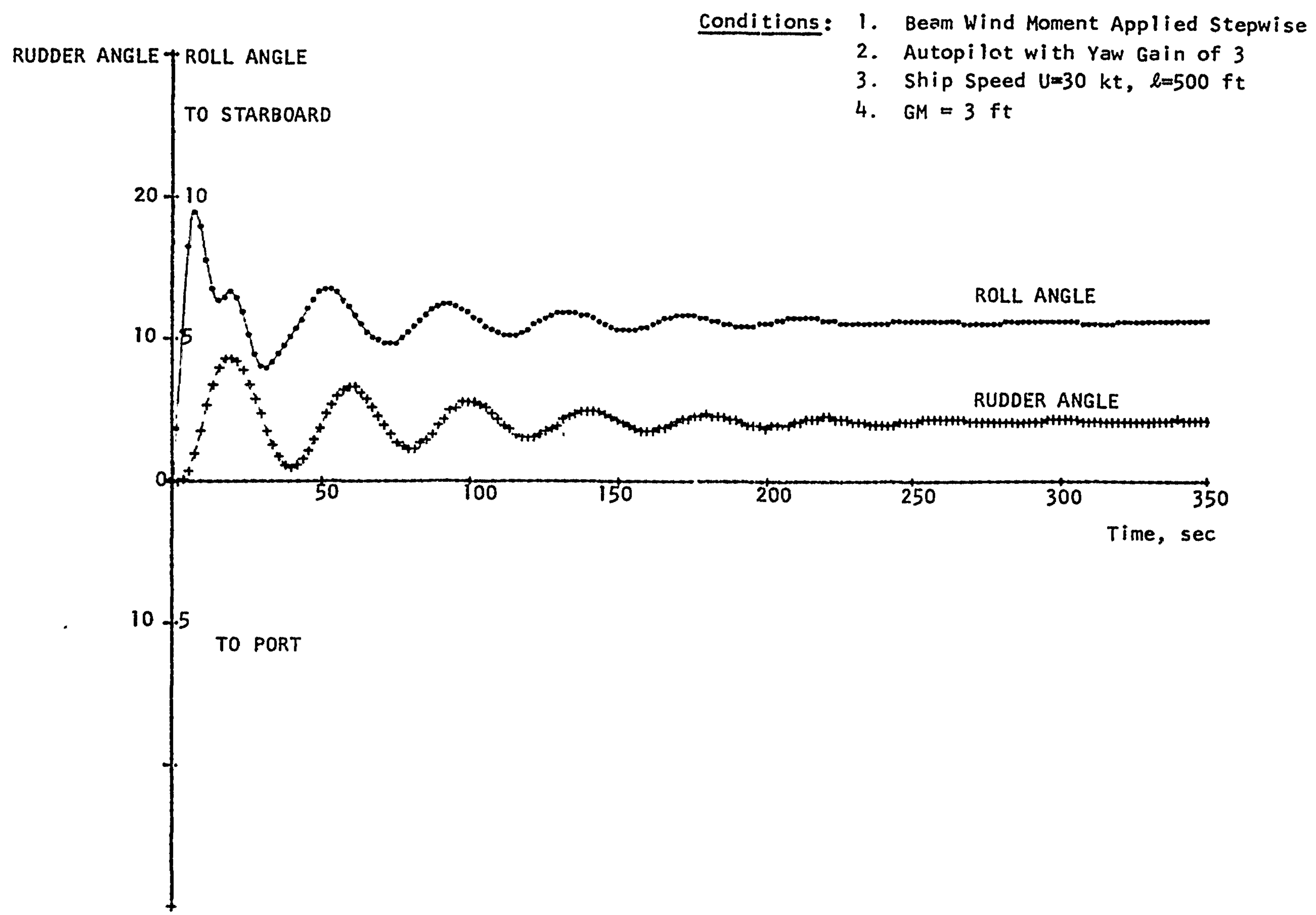


FIGURE 14. ROLL-YAW-RUDDER COUPLED MOTION

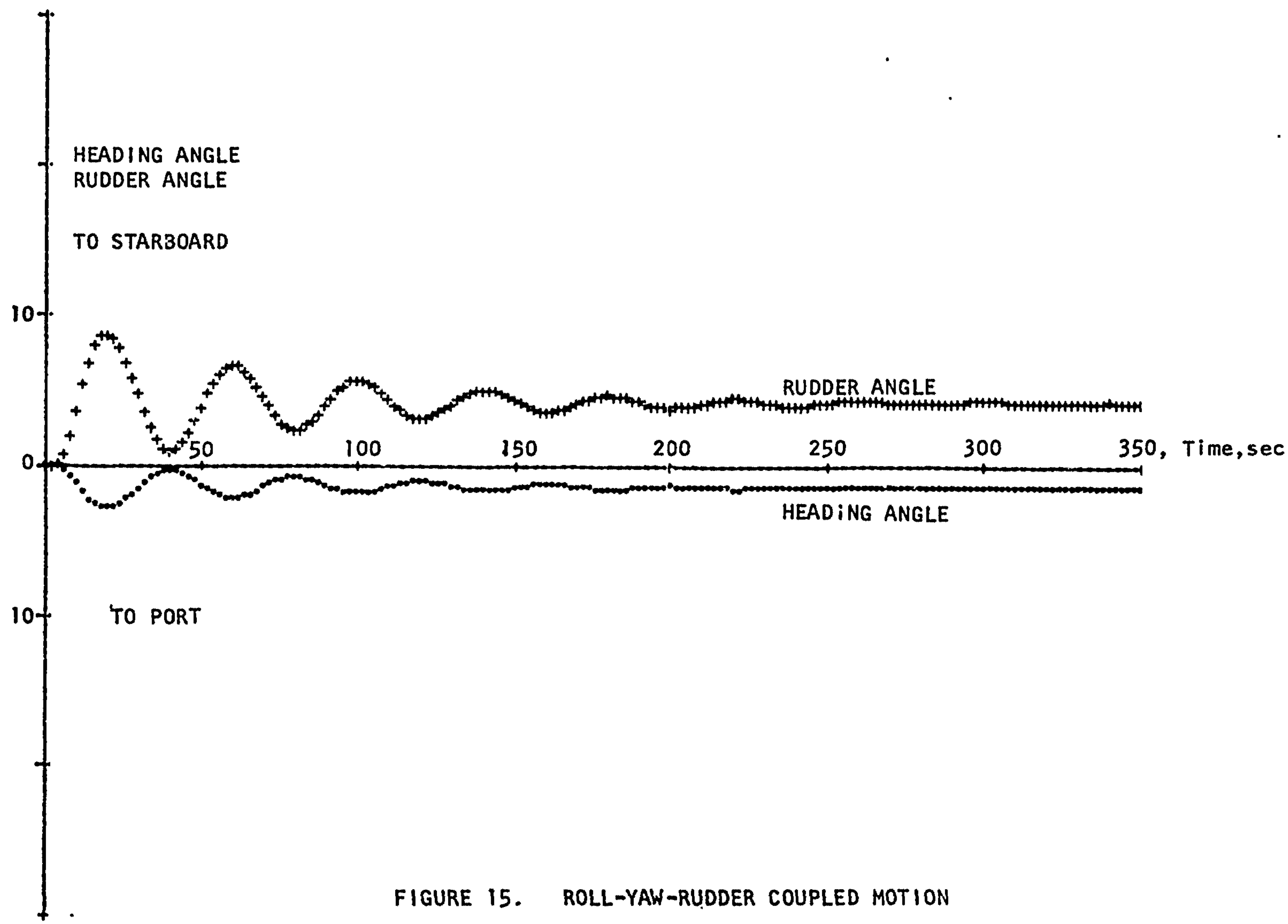


FIGURE 15. ROLL-YAW-RUDDER COUPLED MOTION

<u>Conditions:</u>
1. Beam Wind Moment Applied Stepwise
2. Autopilot with Yaw Gain of 3 and Yaw-Rate Gain of 0.5
3. Ship Speed U=30 kt, ℓ=500 ft
4. GM = 3 ft

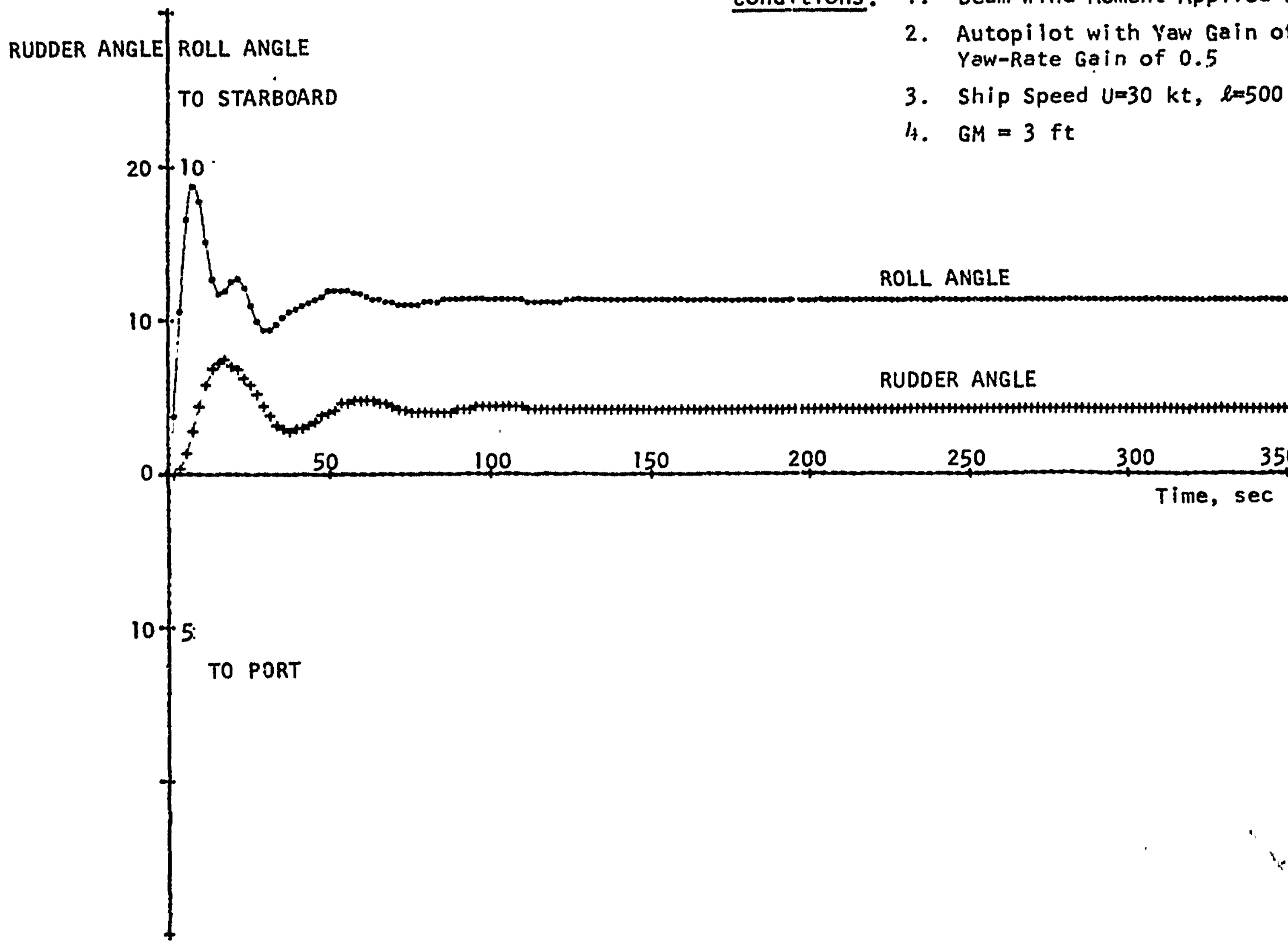


FIGURE 16. ROLL-YAW-RUDDER COUPLED MOTION

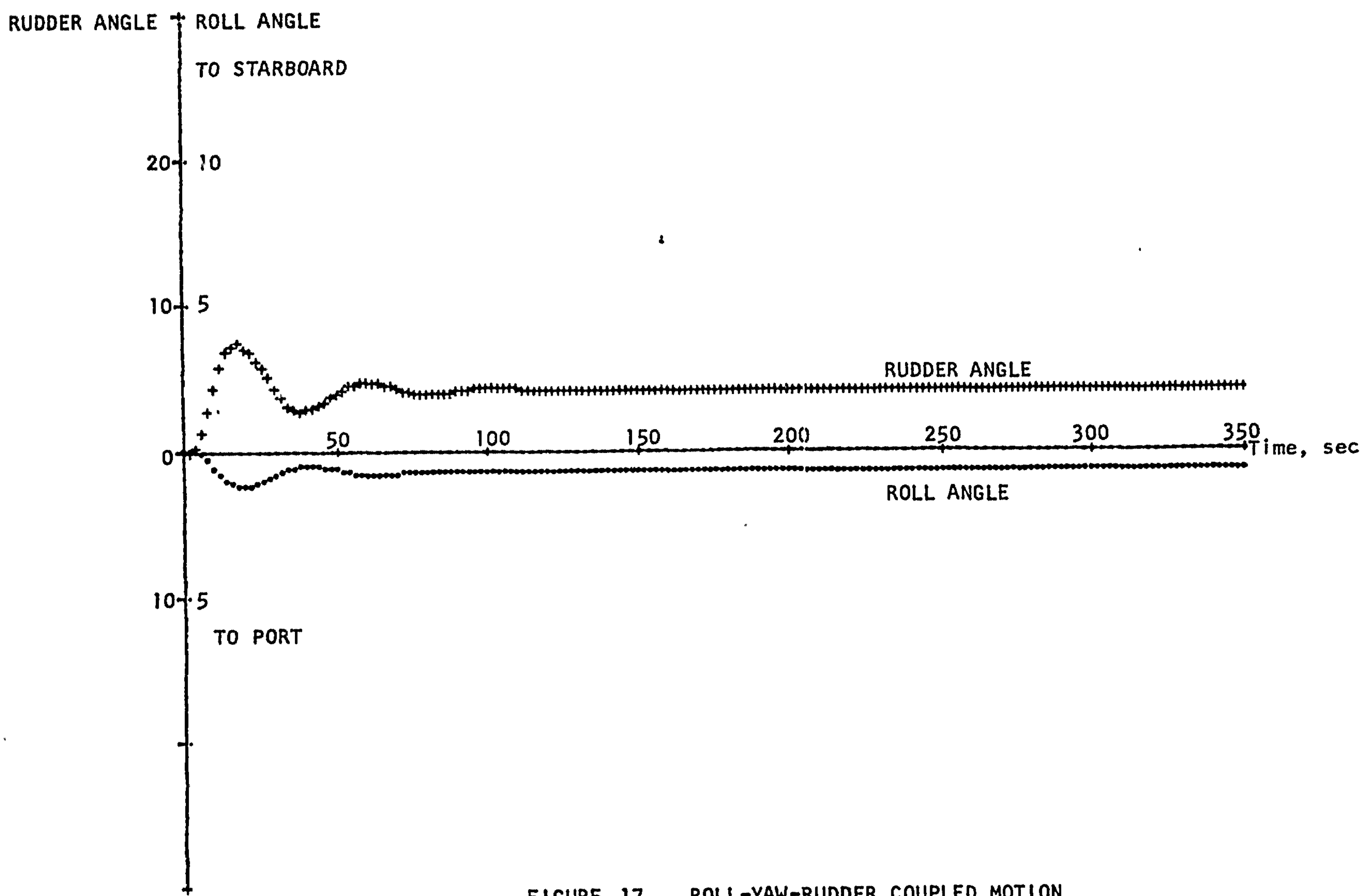


FIGURE 17. ROLL-YAW-RUDDER COUPLED MOTION

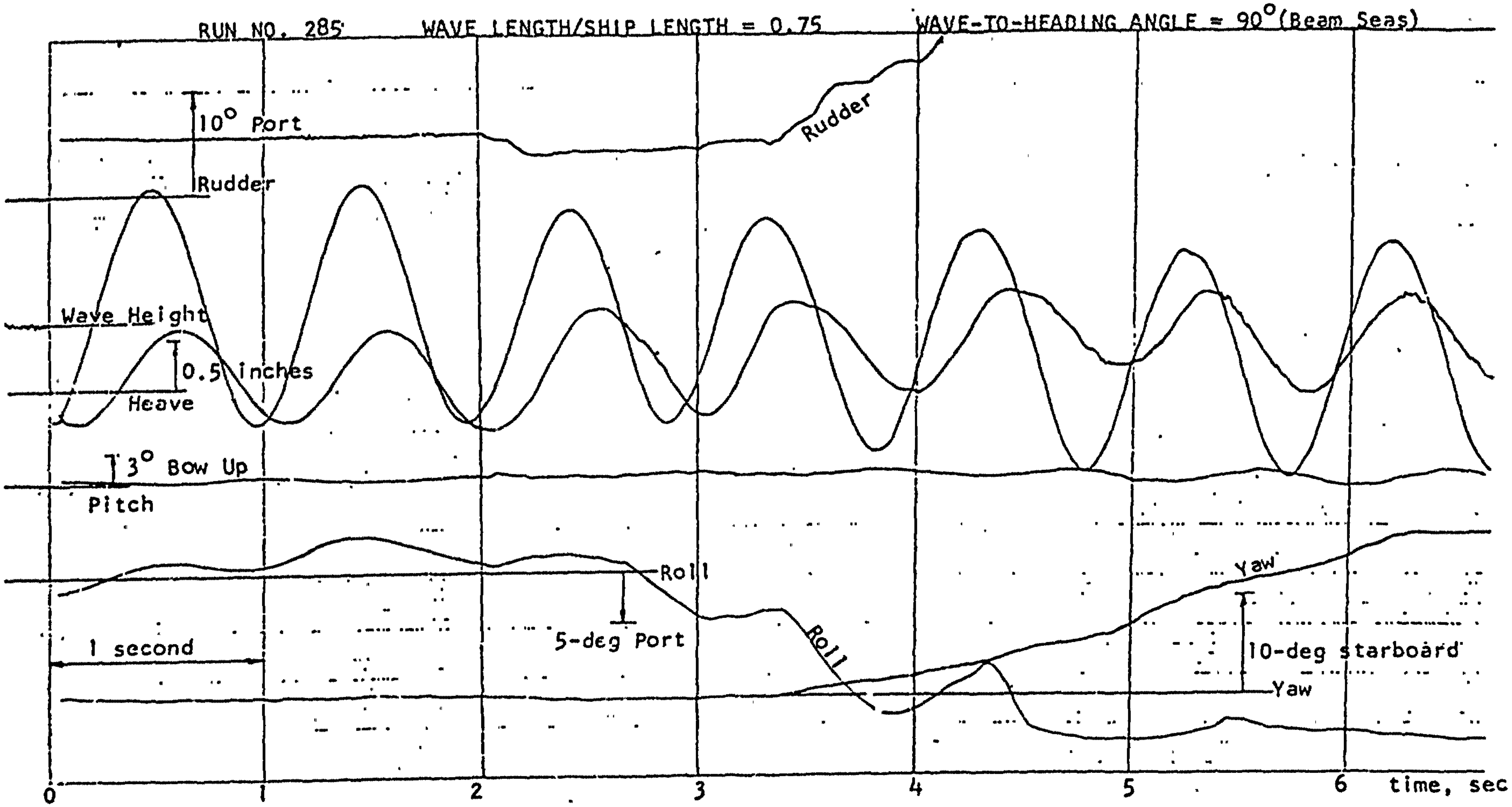


FIGURE 18. TEST RECORDS OF YAW, ROLL, AND RUDDER OF A CONTAINER SHIP MODEL (6.29-ft long) IN A BEAM SEA, INDICATING YAW INSTABILITY AND COUPLING BETWEEN YAW, ROLL AND RUDDER.

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